# PROTO-CLUSTERS ASSOCIATED WITH RADIO GALAXIES FROM $Z$ = 2 TO $Z$ = 4

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**Abstract**

We have carried out narrow band imaging targeted at the Ly$\alpha$ line of emitters associated with radio galaxies at $2 < z < 5$. Subsequent spectroscopy has confirmed the identity of $> 120$ Ly$\alpha$ emitters and led to the discovery of six proto-clusters up to $z = 4.1$ with velocity dispersions between 300 and 1000 km s$^{-1}$. The number of emission line galaxies in the observed fields is four to fifteen times higher than in blank fields. These results strongly support the idea that high redshift radio galaxies are the progenitors of central brightest cluster galaxies located in the progenitors of clusters of galaxies.

## 1. Introduction

Observational studies of cosmological structures can never be complete without the full picture provided by multi wavelength explorations, but in the case of the search for very high redshift clusters or their progenitors the use of multi wavelength observations is particularly fruitful. The detection of galaxy aggregations using conventional optical and X-ray becomes difficult at $z > 1$ due to the presence of many fore- and background objects and/or the surface brightness dimming of the extended emission. Several lines of observation indicate that powerful radio galaxies, as are found up to $z = 5.2$, are located within regions of high galaxy density. The technique of narrow band imaging can detect a group of emission line galaxies at a narrow high redshift range.

Applying this technique to fields containing high redshift galaxies, we succeed to find galaxy groups at high redshift. The groups will be used to study cluster progenitors, its galaxies and the massive radio galaxy hosts.

## 2. Sample and observations

We had initially selected ten high redshift radio galaxies (HzRGs, $z > 2$) from our compendium of about 150 $z > 2$ radio sources, many of which have been found in the Leiden survey of steep spectrum radio sources (Röttgering et al., 1994; De Breuck et al., 2000). We have succesfully observed six fields and during an extension of the program, also the field of the most distant known radio galaxy, at $z = 5.19$, bringing the total number of nights allocated to this VLT Large Program to twenty. The observing time was more or less evenly distributed over imaging and the subsequent multi object spectroscopy, both carried out with the FORS2 instrument. The detector of this instrument has a field of view of almost $7 \times 7$ arcminutes (about $3 \times 3$ Mpc at $z > 2$). For the two highest redshift sources custom narrow band filter were manufactured. For the others we have used available FORS filters. In the following, two observed fields will be described in more detail and a summary of the results of the program will be presented.

## 3. Early results I: MRC 1138−262 at $z = 2.16$

This radio galaxy was the target of our pilot study carried out with FORS1 at the VLT. It is exceptionally suitable as it manifests many of the properties which indicate a rich environment, namely the highest radio rotation measure in a sample of 80 HzRGs and a very distorted radio morphology (Carilli et al., 1997), a very clumpy UV morphology (Pentericci et al., 1997), a large and luminous Ly$\alpha$ halo ($\sim$ 150 kpc, Kurk et al., 2000a), and extended X-ray emission (Carilli et al., 2002). In addition, its redshift of 2.16 is near the lower limit where detection of Ly$\alpha$ emission with ground based facilities is possible. Narrow band imaging of the field of 1138−262 resulted in the detection of 50 candidate Ly$\alpha$ emitters (LAEs, Kurk et al., 2000b). Multi object spectroscopy of these candidates confirms the presence of a single emission line at the expected wavelength for fifteen objects (Pentericci et al., 2000). One of these is an AGN as shown by the broadness of its emission line (FWHM $\sim$ 6000 km s$^{-1}$). The others seem to form two dynamical groups with velocity dispersions of $\sim$ 200 and 400 km s$^{-1}$ (if regarded as one group the dispersion is $\sim$ 1000 km s$^{-1}$). The volume density of LAEs is about four times higher than that measured for the blank field population of LAEs (Steidel et al., 2000). In addition to the observations necessary to identify the LAEs, we have obtained imaging in a number of optical and infrared bands with FORS and ISAAC at the VLT, one of which is a narrow band filter in the NIR targeted at redshifted H$\alpha$ emission

of galaxies associated with 1138−262. Excess narrow band flux testifies the presence of 40 candidate H$\alpha$ emitters in the field (Kurk et al., 2003). Long slit ISAAC spectroscopy of nine candidates shows that three objects exhibit emission lines identified as H$\alpha$ and [NII] while the remaining six objects have fainter single lines consistent with the identification with H$\alpha$, one of which has a FWHM of $\sim$ 5000 km s$^{-1}$ revealing another AGN at $z = 2.16$. The two AGN discovered with the narrow band technique are part of a larger group of five AGN probably associated with the radio galaxy as shown by Chandra observations of the field (Pentericci et al., 2002). The number density of soft X-ray sources detected by Chandra is in excess of that found in other fields. The detected overdensities of Ly$\alpha$, H$\alpha$ and X-ray emitters draw a consistent picture of a powerful radio galaxy in an aggregation of galaxies which may form a cluster of galaxies.

## 4. Early results II: TN J1338−1942 at $z = 4.11$

With regard to both its continuum and Ly$\alpha$ emission, TN J1338−1942 is amongst the most luminous radio galaxies known. Its Ly$\alpha$ line profile and radio morphology are very asymmetric indicating strong interaction with dense gas (De Breuck et al., 1999). Based on the line equivalent width derived from the narrow and broad ($R$) band images and also on the absence of emission in the broad $B$ band, 28 objects in the field of 1338−1942 were selected as candidate LAEs (Venemans et al., 2002). Of the 23 candidates subsequently observed spectroscopically, 20 show a single emission line in the expected wavelength range. The identification of the observed features with lines other than Ly$\alpha$ can be excluded in practically all cases. The velocity distribution of the emitters has a dispersion of 326 km s$^{-1}$, significantly smaller than expected from a random distribution of emitters selected with the narrow band filter. Compared with the LALA survey (Rhoads et al., 2000), the volume density of LAEs is about fifteen times larger than in a blank field. The spatial distribution of emitters is not homogeneous over the observed field. The radio galaxy is not in the center of the observed structure but rather at the northern edge.

## 5. High redshift proto-clusters and radio galaxies

At the time this talk was delivered, six HzRG fields were observed sufficiently deep to assess the density of companion LAEs. In the fields of HzRGs at $z$ = 2.86, 2.92, 3.13 and 3.14 the number of candidate (and spectroscopically confirmed) emitters are: 52 (37), 70 (30), 78 (31) and 20 (11), which amounts to over-densities of 4 to 15. The velocity dispersion of the ensembles of emitters observed decreases with increasing redshift: from $\sim$ 1000 km s$^{-1}$ at $z = 2$ to $\sim$ 325 km s$^{-1}$ at $z = 4$. It would be premature to draw conclusions on this result, however, as there are only six data points. The size

of the structures of LAEs is in all cases larger than the field sampled: $> 3$ Mpc (comoving) and seems sometimes bound in one direction. We have compared the number of spikes in the redshift distribution of Lyman Break Galaxies (LBGs) at $2.7 < z < 3.4$ (Steidel et al., 1998) with the number of powerful ($P_{2.7\,\mathrm{GHz}} > 10^{33}$ erg s$^{-1}$ Hz$^{-1}$ sr$^{-1}$) radio galaxies in this redshift range (Dunlop & Peacock, 1990). Assuming that the radio sources are active only once for a period of $\sim 10^7$ year, the numbers are consistent with every LBG redshift spike being associated with a massive galaxy that has been or will become a luminous radio source once.

From the preliminary results we derive the following conclusions: narrow band imaging is an efficient technique to find galaxy over-densities in a narrow redshift range, HzRGs are excellent tracers of these over-densities and may be the progenitors of central brightest cluster galaxies located in the progenitors of clusters of galaxies.

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